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Bose-Einstein correlations in proton-proton collisions using a fluid dynamical scenario

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Using a fluid dynamical scenario for pp scattering, we compute Bose-Einstein correlation functions for pion pairs and extract the femtoscopic radii. The calculations are compared to the results from the measuremnets in pp collisions at the LHC obtained at the centre of mass energy of 0.9 and 7 TeV with the ALICE detector.

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Recently, first results on the dependence on average pion-pair transverse momentum k_T of the femtoscopic radii in pp collisions at $\sqrt{s}$ = 7 TeV have been obtained for different multiplicity classes [1]. Interestingly, one observes a more and more visible decrease of the radii with k_T with the multiplicity increase, similar to that observed in heavy ion collisions. Moreover, the radii increase with multiplicity, reminding the increase of the radii with centrality in heavy ion collisions. A reasonable question is: is there the same dynamics in proton-proton and heavy ion collisions? Could it be that a collective expansion driven by hydrodynamics is present in pp scattering as well?

In this report, to find an answer to these questions, we postulate a scenario of hydrodynamic evolutions based on flux-tube initial conditions, and compute correlation function. Then, we apply the same fitting procedures it is done experimentally, and analyze the k_T-dependence of the femtoscopic radii.

Originally the hydrodynamics was thought to be a valid description for almost central collisions of heavy nuclei only, where the volume is (relatively) large. However, it seems that this approach works well enough for all centralities. Moreover, no dramatic differences were seen between CuCu data and AuAu ones, although the copper system is much smaller. This points that systems being much smaller than central AuAu may fit well into the fluid picture.

Is a fluiddynamic scenario a nuclear phenomenon? Or can it be formed in pp scattering, as proposed earlier [2, 3, 4, 5, 6, 7]? We will treat proton-proton scattering in the same way as heavy ions, namely incorporating a hydrodynamic evolution. This approach makes clear predictions for many variables, so measurements can justify on the approach. It will be extremely interesting to think about the implications of such a mini QGP, how such small systems as proton-proton ones can equilibrate so quickly, and so on.

What makes pp scattering at LHC energies interesting in this respect, is the fact that at this high energy multiple scattering becomes very important, where a large number of scatterings amounts to a large multiplicity. In such cases, very large energy densities occur, even bigger than the values obtained in heavy ion collisions at RHIC – but in a smaller volume. Several authors discussed already the possibility of a hydrodynamical phase in pp collisions at the LHC, to explain the global distributions, the ridge correltion effect, or to predict elliptical flow [6, 8, 9, 10, 5, 11, 12, 13, 14, 15].

We employ a sophisticated hydrodynamical scenario, first presented in ref. [16] where many details can be found. The following main features are considered:

- the initial conditions obtained from a flux tube approach (EPOS), compatible with the string model used since many years for elementary collisions (electron-positron, proton proton), and with the color glass condensate picture [17];
- the event-by-event procedure, which takes into account the highly irregular space structure of single events, experimentally visible via the so-called ridge structures in two-particle correlations;
- the core-corona separation, considering the fact that only a part of the matter thermalizes [18]; only in the core region, the energy density from the strings is considered for the hydrodynamical evolution;

- use of an efficient code for solving the hydrodynamic equations in 3+1 dimensions, including the conservation of the baryon number, strangeness, and electric charge;
- a realistic equation-of-state, compatible with lattice gauge results – with a cross-over transition from the hadronic to the plasma phase [19, 20];
- a complete hadron resonance table, making our calculations compatible with the results from statistical models;
- hadronic cascade procedure after hadronization from the thermal system at an early stage [21, 22].

In ref. [16], we test the approach by investigating all soft observables of heavy ion physics, in case of AuAu scattering at a c.m. energy of 200 AGeV. In refs. [7, 6] we investigate the proton-proton LHC results, with the "ridge effect" among them.

In the following we discuss first pp scattering at 7 TeV. We consider several multiplicity classes, named *mult 1*, *mult 4* , *mult 7* and *mult 8*, corresponding to four out of the eight multiplicity classes used in ref. [1], going from low multiplicity (*mult 1*, less than minimum bias) to high multiplicity (*mult* 8, five times minimum bias). Our core-corona procedure finds no core for *mult 1,* then increasing core fraction, and for *mult 4* to *mult 8* essentially 100% core, with increasing energy densities. One might conclude that the mult 1 events are the strings which expand longitudinally, whereas mult 4 to mult 8 events show a hydrodynamical expansion, also in transverse direction. The energy density increases with multiplicity, values of more than 100 GeV/fm^3 are achieved. We consider two options for the equation of state (EoS), one being a parametrization of the results of [19], and the other one referring to [20]. There is a big difference between the two; the transition temperature is much lower and the transition is much smoother in[19], compared to [20]. Correspondingly, the “freeze out” radii (where the transition hydro / cascade enters) are very different within these two models. However, the final results differ less, because the early freeze out for the EoS from [19] is followed by an intense hadronic rescattering.

Based on roughly ten million simulations of the hydrodynamical evolution, we compute in the usual way the correlation functions for $\pi^+\pi^+$ pairs, taking into account Bose-Einstein statistics, as discussed in [7, 16, 23]. Whereas in the data a model (like PYTHIA) has to be used as the “baseline”, we stay consistently within our scenario and use simply a calculation without Bose-Einstein statistics as baseline. We then fit the correlation functions to obtain the radii. Before showing the results, let us discuss in a qualitative way why we expect a decrease of the radii with k_T (see also the discussion in ref [24]). Let us consider the freeze out procedure: Most particle production occurs in the region where the radii drop to zero. Comparing two radii, we have to recall that the collective flow at a large radius is much bigger compared to small radius. Consider the corresponding momentum vectors of pairs, emitted at large and small radii (which finally amounts to large and small k_T), where the vectors of a pair are such that their difference is the same. The space distances in case of a small radius are then bigger than the ones in case a large radius (and these distances are essentially the femtoscopic radii).

Let us discuss our main result: As seen in fig. 1, all radii indeed show a more and more pronounced decrease with increasing k_T, for data and simulations, which can – in the calculations

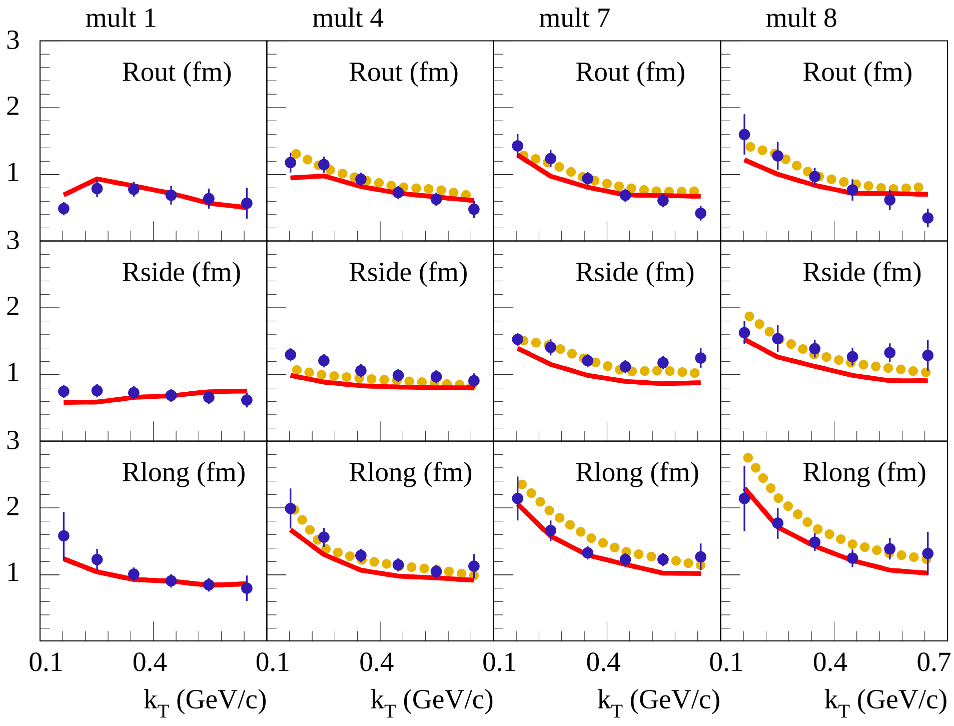

Figure 1: (Color online) Preliminary results (EPOS2.12) for femtoscopic radii for three different multiplicity classes, using an EoS compatible with ref. [19] (solid curves) and with ref. [20] (dotted curves). The curves are the same for *mult 1* because there is no fluid phase. The points show the experimental results obtained in [1] for pp collisions at 7 TeV by ALICE. The curves are absolute predictions, the parameters of the model are obtained from other comparisons (yields, p_t spectra).

– clearly be attributed to collective flow. For the case *mult 1* the radii R_{out} and R_{side} are essentially flat, only R_{long} has already some k_T dependence. So we see here nicely the transition from a longitudinal expansion (string) towards a three-dimensional hydrodynamical expansion for higher multiplicities.

At lower LHC energies (0.9 TeV), a fluid dynamical scenario seems to be favored as well [7]. We investigate again $\pi^+\pi^+$ correlations. In figs. 2 and 3, we show the correlation functions for different k_T intervals defined as (in MeV): KT1$=[100,250]$, KT3$=[400,550]$. We compare the three different scenarios: “full calculation” (solid line), “calculation without hadronic cascade” (dashed), and “calculation without hydro and without cascade” (dotted), and data from ALICE [25]. The data are actually not Coulomb corrected, because the effect is estimated to be small compared to the statistical errors. Here we consider the highest multiplicity density class with $dn/d\eta(0) = 11.2$, which is close to the value of 12.9 from our simulated high multiplicity events. We compare with the real data (not polluted with simulations), normalized via mixed events, and we do the same with our simulations. Despite the limited statistics, in particular at large k_T, we see very clearly that the “full” scenario, including hydro evolution and hadronic cascade, seems to fit the data much better then the two other ones.

We conclude that in pp collisions at 0.9 and 7 TeV, a hydrodynamical scenario is well supported

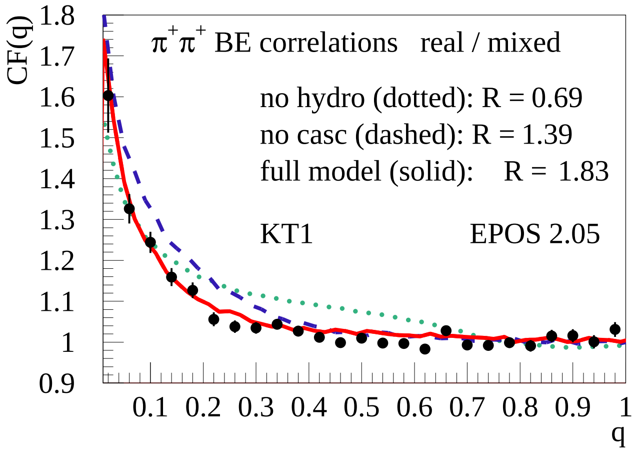

Figure 2: (Color online) The correlation functions *CF* for $\pi^+ - \pi^+$ pairs in pp collisions at 0.9 TeV as obtained from our simulations, for the three different scenarios, for k_T bin KT1, compared to data from ALICE [25] (points).

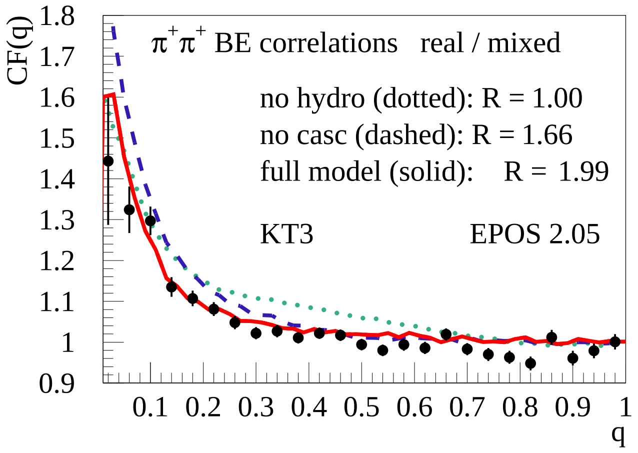

Figure 3: (Color online) Same as fig. 2, but k_T range KT3.

by the data on correlation functions and femtoscopic radii.

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